



INVESTOR IN PEOPLE

The Patent Office
Concept House
Cardiff Road
Newport
South Wales
NP10 8QQ

PRIORITY DOCUMENT

SUBMITTED OR TRANSMITTED IN
COMPLIANCE WITH RULE 17.1(a) OR (b)

RECEIVED
16 AUG 2004

I, the undersigned, being an officer duly authorised in accordance with Section 74(1) and (4) of the Deregulation & Contracting Out Act 1994, to sign and issue certificates on behalf of the Comptroller-General, hereby certify that annexed hereto is a true copy of the documents as originally filed in connection with the patent application identified therein.

In accordance with the Patents (Companies Re-registration) Rules 1982, if a company named in this certificate and any accompanying documents has re-registered under the Companies Act 1980 with the same name as that with which it was registered immediately before re-registration save for the substitution as, or inclusion as, the last part of the name of the words "public limited company" or their equivalents in Welsh, references to the name of the company in this certificate and any accompanying documents shall be treated as references to the name with which it is so re-registered.

In accordance with the rules, the words "public limited company" may be replaced by p.l.c., plc, P.L.C. or PLC.

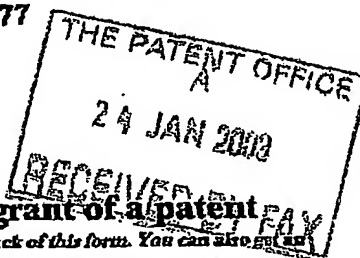
Re-registration under the Companies Act does not constitute a new legal entity but merely subjects the company to certain additional company law rules.

Signed

Dated 9 August 2004

CERTIFIED COPY OF
PRIORITY DOCUMENT

Patents Form 1/77

Patents Act 1977
(Rule 18)The
Patent
Office24JAN03 E779771-1 002831
P01/T700 0.00-0301664.9**Request for grant of a patent**

(See the notes on the back of this form. You can also ask for an explanatory leaflet from the Patent Office to help you fill in this form)

The Patent Office

Cardiff Road
Newport
South Wales
NP9 1RH

1. Your reference

57.0547 GB NP

24 JAN 2003

2. Patent application number

(The Patent Office will fill in this part)

0301664.9

3. Full name, address and postcode of the or of each applicant (underline all surnames)

Schlumberger Holdings Limited

PO Box 71
Craigmuir Chambers
Road TownTortola
British Virgin Islands

Patents ADP number (if you know it)

If the applicant is a corporate body, give the country/state of its incorporation

British Virgin Islands

226326001

4. Title of the invention

System and method for inferring geological classes

5. Name of your agent (if you have one)

"Address for service" in the United Kingdom to which all correspondence should be sent (including the postcode)

Christophe MACQUET
Intellectual Property Law Department
Schlumberger Cambridge Research Limited
High Cross
Maddingley Road
Cambridge CB3 0EL
United Kingdom

Patents ADP number (if you know it)

443350400

6. If you are declaring priority from one or more earlier patent applications, give the country and the date of filing of the or of each of these earlier applications and (if you know it) the or each application number

Country

Priority application number
(if you know it)Date of filing
(day / month / year)

7. If this application is divided or otherwise derived from an earlier UK application, give the number and the filing date of the earlier application

Number of earlier application

Date of filing
(day / month / year)

8. Is a statement of inventorship and of right to grant of a patent required in support of this request? (Answer 'Yes' if:

YES

- a) any applicant named in part 3 is not an inventor, or
 - b) there is an inventor who is not named as an applicant, or
 - c) any named applicant is a corporate body.
- See note (d))

Patents Form 1/77

Patents Form 1/77

5. Enter the number of sheets for any of the following items you are filing with this form. Do not count copies of the same document

Continuation sheets of this form -

Description 23

Claim(s) 1

Abstract 1

Drawing(s) 5

10. If you are also filing any of the following, state how many against each item.

Priority documents -

Translations of priority documents -

Statement of inventorship and right to grant of a patent (Patents Form 7/77) 1 ✓

Request for preliminary examination and search (Patents Form 9/77) -

Request for substantive examination (Patents Form 10/77) -

Any other documents -
(please specify)

11. I/We request the grant of a patent on the basis of this application.

Signature

Date

24 January 2003

12. Name and daytime telephone number of person to contact in the United Kingdom
Christophe Macquet
01223 325268

Warning

After an application for a patent has been filed, the Comptroller of the Patent Office will consider whether publication or communication of the invention should be prohibited or restricted under Section 22 of the Patents Act 1977. You will be informed if it is necessary to prohibit or restrict your invention in this way. Furthermore, if you live in the United Kingdom, Section 23 of the Patents Act 1977 stops you from applying for a patent abroad without first getting written permission from the Patent Office unless an application has been filed at least 6 weeks beforehand in the United Kingdom for a patent for the same invention and either no direction prohibiting publication or communication has been given, or any such direction has been revoked.

Notes

- If you need help to fill in this form or you have any questions, please contact the Patent Office on 0645 500505.
- Write your answers in capital letters using black ink or you may type them.
- If there is not enough space for all the relevant details on any part of this form, please continue on a separate sheet of paper and write "see continuation sheet" in the relevant part(s). Any continuation sheet should be attached to this form.
- If you have answered 'Yes' Patents Form 7/77 will need to be filed.
- Once you have filled in the form you must remember to sign and date it.
- For details of the fee and ways to pay please contact the Patent Office.

Patents Form 1/77

57.0547 UK

DISPATCH

- 1 -

System and method for inferring geological classes

FIELD OF THE INVENTION

5

This invention relates the enhancements of neural network-assisted reservoir characterization techniques for geological classification from measured input data.

- 10 According to the present invention, the terms "measured input data" or "INPUT DATA" refers to, in particular, downhole logs. The set of logs used in the testing of the method of the invention includes gamma ray (GR), sonic slowness (DT), thermal neutron porosity (NPHI), bulk density (RHOB) and true
15 resistivity (RT), all measured at same depth for each sample, and at a constant sampling distance. However, INPUT DATA are not restricted to samples at a single depth. Alternatively, attributes that represent, for example, sliding window averages or other statistics taken over a depth range in the neighborhood
20 of the depth of interest, can be constructed. 2D image logs (e.g., FMI) or 3D seismic cubes are also encompassed.

According to the present invention, the terms "geological classes" or "CLASSES" refers to, principally, the rock facies
25 (lithofacies) or the reservoir rock types. However, any other discrete classification of geological features (e.g. petrophysical properties) is possible.

PRIOR ART

30

Rock facies class prediction by neural network processors applied to downhole logs is an existing method developed in the nineteen nineties which gave rise to several publications [1].

57.0547 UK

- 2 -

For instance, it has been implemented by an ENI AGIP E&P team, and integrated in a joint development project into the product *RockCell™* within the Schlumberger™ *GeoFrame™* oilfield interpretation software platform.

5

For rock facies estimation, a set of single-channel log curves are selected. Typical logs used are gamma ray (GR), sonic slowness (DT), thermal neutron porosity (NPPI), and bulk density (RHOB), but this list is not limited. New attributes can also be
10 generated from existing logs in order to reveal additional features in the logs.

A current limitation in analyzing geological measured data such as downhole logs, is that their relationship to classes such as
15 rock facies is not obvious. In each borehole, there are unknown local factors that may affect the data in unexpected ways. It can thus be risky to classify on a simplified theoretical analysis or by data clustering. There is a need for a method to identify associations between input data and to build implicit
20 complex functional relationships. A "learn from examples" method is more preferred to building an expert system. The discovered methods would then be used to predict the classes and their associated probabilities.

25 An Artificial Neural Network (ANN) scheme has been developed to implement learning by example as applied to downhole geological classification. Neural networks can "learn" specific computation schemes. Once trained, a neural network can find acceptable solutions on any set of data referring to the learned schemes.
30 This gives artificial neural networks an ability to generalize from training experience (see [12]). Unlike analytical approaches such as statistics, neural networks require no explicit computational model, and are not limited by a lack of

- 3 -

normality or the non-linearity of the physical phenomenon. As a consequence, they "learn" relationships between data that may be hard to discover with analytical methods.

5 The behavior of a neural network is defined by its architecture. This architecture consists of the way its neurons (individual computing elements) are connected and by strength (weight) of those connections. Each neuron performs a weighted sum (linear combination) of its inputs, then applies an almost non-linear
10 activation function, to finally produce an output. The resulting output of a given neural layer is forwarded to the next layer and so on through the network. In other words, neural networks plainly perform a massively parallel set of elementary computations. Whereas the weights vary the strength of
15 connections from one node to another, the sigmoidal activation function provides the highly non-linear property of neural data processing.

The main advantage of those neural nets is their learning
20 capability. During the learning phase, given a training set of data, the interconnection weights are gradually adjusted so as to stabilize the network's output, and, in the case of the supervised learning, to minimize the mean square error between the effective output and the desired one. The preferred
25 implementation of the NN is a supervised feed-forward, multi-layer perceptrons trained with the back-propagation algorithm.

Methods and techniques used today are able to classify without the a priori knowledge of classes sequencing. The prediction
30 operates on geological input data sample-by-sample, and produces for each input pattern the probabilities of the most likely classes.

57.0547 UI

- 4 -

However, this system sometimes fails in its predictions. One of its main limitations is that it does not honour geological prior knowledge. Some of the predictions fail due to the fact that geologically improbable classes transitions are often observed.

5

Sedimentologists have observed that the vertical and lateral sequence of geological facies¹ seen in outcrop and in the subsurface are not random. Since the stratigraphic layering in the earth represents successive time of deposition, the rock record actually represents a time series of events. Since the normal neural net techniques make sample-by-sample predictions, they do not consider previous states of prediction (e.g., the facies predicted at location X_{n-1} , which implies t_{n-1} , constrains the prediction at location X) and they fail to take advantage of likely non-random transitions between lithology or facies. Geology can provide strong constraints on the prediction of stratigraphic successions. Sedimentologists have long invoked Markov models for analyzing the vertical and lateral sequences [2, 3, 4, 5]. Therefore, using a Markov scheme using geological prior information of rock facies transition probabilities seems a fruitful way to improve the prediction of the neural network scheme.

Systems for speech recognition, integrating a neural network and a Hidden Markov Model (HMM), are known from the state of the art. HMMs are used as a major approach in the majority of continuous speech recognition systems. They provide an accurate and reliable framework for segmentation and classification of speech. HMM states can stand for the phone classes, c_i (e.g., phonemes) to be identified, whereas the HMM observation sequence for the acoustic vectors y (e.g., a combination of cepstral and energy acoustic parameters). As a consequence, the state sequence $X = x_1, x_2, \dots, x_T$ of length T can be considered as

57.0547 UK

- 5 -

the "sentence" to be recognized due to the recorded and discretized acoustic observation sequence $Y = Y_1, Y_2, \dots, Y_T$.

Facies sequences have been considered as analogous to the phoneme sequences in the speech recognition methods. The HMM and its stochastic behavior represent the allowed or forbidden transitions between geological classes and their associated probabilities, and the geological input data are analogous to the acoustic observation vectors used during the speech recognition process.

The HMM technology has already been applied to lithofacies classification from well logs. Publications [6], [7] and [8] describe the building, training and application of a Hidden Markov Model to estimate the lithology of uncored boreholes based on key learning data sets where the lithology is known. In those methods, the lithofacies sequence stands for the consecutive states of the HMM, and the log data for the observations. Those methods do not rely on the use of a neural network. This means they are able to model the stochastic character of rock facies transitions and the rock facies sequences. However, they perform poorly while modeling the non-linear relationship between logs and rock facies, as they do not benefit from the complex neural network architectures and computation schemes.

In the papers [9] and [10], and in several patents concerning speech recognition, such as [11], an interesting approach to classify speech phonemes has been developed by the use of hybrid models mixing both HMM and ANN. Those approaches enable speech recognition systems to cope with the strong statistical assumptions of the HMMs.

57.0547

- 6 -

Applying a feed-forward neural network to the input data y can give us estimates of the conditional posterior probabilities $p(x_i/y)$ of each class x_i , given the current input vector y . Those class-conditional posterior probabilities must sum to one, and therefore need to be normalized. However, a HMM needs the conditional prior probabilities $p(y/x_i)$. Assuming there are enough training data and that the training does not get held up in poorly performing local minima, the feed-forward neural network is able to approximate the prior probabilities thanks to Bayes' rule. Indeed, $p(y/x_i) = p(x_i/y) \times p(y) / p(x_i)$. The prior probability distribution of classes is context-dependent but can be estimated by counting the classes occurrence of classes in the learning set, or by introducing prior knowledge. The prior probability of the observation vector can be discarded as for each time step; it is independent of the phone class.

The HMM and observation sequence finally provide, thanks to the Viterbi algorithm, the most likely state sequence which caused the observed acoustic data sequence.

20

References Cited

- [1] Hall J., Scandella L. (1995). "Estimation of Critical Formation Evaluation Parameters Using Techniques of Neurocomputing", Society of Professional Well Log Analysts Annual Logging Symposium, 36th, Paris, France, 1995, Transactions, p. PPP1-PPP12.
- [2] Gingerich, P. D. (1969). "Markov analysis of cyclic alluvial sediments." Journal of Sedimentary Petrology 39: 330-332.
- [3] Miall, A. D. (1973). "Markov chain analysis applied to an ancient alluvial plain succession." Sedimentology 20: 347-364.
- [4] Carr, T. R. (1982). "Log-linear models, markov chains and

57.0547 UK

- 7 -

cyclic sedimentation." Journal of Sedimentary Petrology 53(2): 905-912.

- [5] Powers, D. W., Easternling, R. G. (1982). "Improved methodology for using embedded Markov chains to describe cyclical sedimentation." Journal of Sedimentary Petrology 52(3): 913-923.
- [6] Eidsvik, J., Mukerji, T, Switzer P. (2002). "Estimation of geological attributes from a North Sea well log : an application of hidden Markov chains", Norges Teknisk - Naturvitenskapelige Universitet, submitted for publication in 2002.
- [7] Schumann A. (2002). "Hidden Markov Models for Lithological Well Log Classification", Freie Universitat Berlin. Presented at the Annual Conference of the International Association for Mathematical Geology, 2002.
- [8] Padron, M., Garcia-Salicetti, S., Barraez, D., Dorizzi, B., Thiria, S. (2002). "A Hidden Markov Model Approach For Lithology Identification From Logs", Institut National des Telecommunications Evry, Univesidad Central de Venezuela Caracas, Universite Pierre et Marie Curie Paris. Submitted for the 3rd Conference on Artificial Intelligence Applications to the Environmental Science, 83rd Annual Meeting of American Meteorological Society, 2003.
- [9] Srivastava S. (2001). "Hybrid Neural Network / HMM Based Speech Recognition", Department for Electrical and Computer Engineering, Mississippi State University, 2001.
- [10] Renals, S., Morgan, N., Boulard, H., Cohen, M., Franco, H. (1994). "Connectionist Probability Estimators in HMM Speech Recognition". IEEE Trans. Speech and Audio Processing, 2:161-175, 1994.
- [11] Albesano, D., Gemello, R., Mana, F., (1996). "Speaker independent isolated word recognition system using neural networks", US Patent 5,566,270, October 15, 1996.
- [12] Bishop C. (1995). Neural Networks for Pattern Recognition, Oxford Press 1995.

57.0547 UK

- 8 -

SUMMARY OF THE INVENTION

The starting point of this invention consists of enhancing the
5 neural networks algorithms to make their predictions more
accurate and robust in oilfield applications.

In a first aspect, the invention concerns a system for inferring
geological classes from oilfield well input data comprising a
10 neural network for inferring class probabilities, characterized
in that said system further comprises means for integrating
class sequencing knowledge and optimising said class
probabilities according to said sequencing knowledge.

15 Preferably, the means for integrating class sequencing knowledge
and optimising said class probabilities according to said
sequencing knowledge comprises a hidden Markov model.

In a second aspect, the invention concerns a method for
20 inferring geological classes from oilfield well input data,
comprising the following steps: - inferring class probabilities
with a neural network; and - integrating class sequencing
knowledge and optimising said class probabilities according to
said sequencing knowledge.

25 Preferably, integrating class sequencing knowledge and
optimising said class probabilities according to said sequencing
knowledge is achieved according to a hidden Markov model.

30 Advantageously, the invention relates to a system and method for
inferring geological classes from single-channel oilfield input
data by applying hybrid neural network hidden Markov models
classifiers.

57.0547 U

- 9 -

The geological classification is inferred using supervised neural networks that are applied to the input data and that predict the associated classes. The vertical class transition constraints are learned within a Markov class transition table and a prior class distribution, which are then reused during the estimation of the classes. This optimizes the predicted class curve and honours geological prior knowledge.

This invention relates the enhancements of artificial neural network (ANN) reservoir characterization techniques for geological classification. Supervised neural network classifiers can be applied to downhole logs to automatically predict lithology or other classes in boreholes. However, ANN systems sometimes infer geologically incorrect vertical (stratigraphic) class transitions within a borehole. The root cause of these errors is the fact the networks analyze and predict the output classes sample-by-sample, without taking the whole borehole sequence of classes into account. Improving the prediction of lithofacies from downhole logs is solved by the system and method of the present invention. In essence, they do not take into account -local information that is commonly important in stratigraphic rock sequences. Geological transitions are commonly not random, but predictably sequenced.

The system outlined here integrates an *a priori* knowledge of class sequencing and of class probability distribution in the neural network predictor. It consists in combining a supervised back-propagation, feed-forward neural network architecture with a Hidden Markov Model module into a complex hybrid neural processing chain. The second processing step optimizes the class stratigraphic sequence. Instead of simply choosing, for each set of input data the class that is the most probable, the chosen class is the one which has both a reasonable occurrence probability given the input data pattern and a reasonable occurrence probability given the previous estimated class. Such

57.0547 UK

- 10 -

a choice governed both by class transition and a posterior class observation probability is implemented through the Viterbi algorithm.

- 5 These and other features of the invention, preferred embodiments and variants thereof, possible applications and advantages will become appreciated and understood by those skilled in the art from the following detailed description and drawings.

10 DRAWINGS

- Figure 1 is a block-diagram of the training of the hybrid ANN-HMM classification system. The training set consists of INPUT DATA across several wells and associated core information.
- 15 The normalization of INPUT DATA and the generation of additional attributes is optional (dotted arrows). The construction of the HMM during the training phase is optional as well, if it is not essential to compute it for the training data set.

- Figure 2 is a block-diagram of the estimation of the hybrid ANN-HMM lithofacies classification system on uncored boreholes
- 20 by applying the system to well logs. The normalization of INPUT DATA and the generation of additional attributes is optional (dotted arrows). As for the HMM, one can load an existing HMM from the data storage system and / or manually define it on the
- 25 basis of the geological prior knowledge.

- Figure 3 is a block diagram of the Hybrid ANN-HMM processing chain in the geological classification estimation mode. The supervised, neural network module aims to predict the posterior class probabilities given an observation. The Viterbi
- 30 processing optimizes the predicted class path.

Figure 4 depicts the same process as in figure 3, but with a state-to-state HMM instead of a sample-by-sample one.

57.0547 UK

- 11 -

Figure 5a shows a particular ANN architecture where the neural network integrates a Kalman-trained matrix K.

Figure 5b illustrates the concept of neural network expert committee.

5

MODE(S) FOR CARRYING OUT THE INVENTION

The Hybrid ANN / HMM is composed of two different components, which are the ANN posterior CLASS probability estimator, and the HMM, comprising only a CLASS transition table and a CLASS probability distribution. Those components are trained separately during the training phase of the system, as they do not need to interfere with one another during the learning step. They are also applied separately during the estimation step.

15

1. Data choice and input

Processing of the INPUT DATA is done on a sample-by-sample basis, and therefore the CLASS probabilities are estimated for each sample.

20

- 1.1. Borehole choice (see step 1.1 to 1.3 on figure 1 and 2.2 on figure 2)

Both the learning and the estimation of the Hybrid HMM / ANN classification system can be done on several wells, as long as they share the same geological INPUT DATA and properties. This system is by consequence designed to propagate the knowledge of the physical and statistical relationships between INPUT DATA and CLASSES, as measured in one or several wells, to the whole set of boreholes within an oilfield.

30

57.0547 UK

- 12 -

If one or more INPUT DATA curves are missing, they can be estimated thanks to available data. One can for instance integrate synthetic logs so as to perform rock class estimation.

- 5 1.2. Input data choice (see step 1.1 on figure 1 and 2.1 on figure 2)

The following section is applicable if we use log curves as INPUT DATA. For the purposes of testing and validating the
10 method outlined here, the set of logs used includes gamma ray (GR), sonic slowness (DT), thermal neutron porosity (NPHT), and bulk density (RHOB), all measured at same depth for each sample, and at a constant sampling distance. A regression is often done
15 on those data, which means that at each depth of interest we take some samples above and some samples below that current depth.

However, any 1D, 2D or 3D information is suitable for this system. A first solution is to extract 1D depth-oriented
20 attributes from the existing information. Another one is to extract sliding window statistics at the neighborhood of the depth of interest, and this can be done for instance on 2D FMI images or 3D seismic cubes.

- 25 1.3. Training data set and cross-validation data set (see step 1.3 on figure 1)

The learning data set must have both INPUT DATA and core or geologist-defined corresponding CLASSES zonation. This CLASSES
30 zonation of the INPUT DATA is considered as the desired goal which has to be attained by the Hybrid HMM / ANN classification system.

57.0547 U

- 13 -

The supervised training of the ANN component is done for each sample of the INPUT DATA, and for as many epochs as necessary, until a global mean square error between the desired outputs and the actual outputs is satisfactory. A second error, the so-called cross-validation error, is also computed on a different data set, not taken into account when training the ANN. This monitors the generalizing abilities of the ANN, preventing the ANN from learning the training data set "by heart". Usually, the training stops when the cross-validation error starts to increase.

The separation between training set and cross-validation set is done on the basis of random choice. The total percentage of data being selected for the cross-validation set is chosen during the ANN architecture choice step, for instance $p = 50\%$. Then, for each sample of the INPUT DATA set, that sample is randomly attributed to the training set or the cross-validation set according to the probability p .

20

1.4. Additional attributes generation (see step 1.4 on figure 1 and 2.3 on figure 2) (OPTIONAL)

As the INPUT DATA may not contain, on a localized sample-by-sample basis, enough spatial information which could help to discriminate among CLASSES, additional information may be extracted from existing data, e.g. seismic data or logs. That information can for instance, show the evolution of the INPUT DATA curves, the energy contained in the curves or the smoothed low-frequency component of the curves. In order to obtain such information one can apply a set of gradients to the INPUT DATA curves, or extract low frequencies thanks to the Fast Fourier

57.0547 UK

- 14 -

Transform, or approximate the INPUT DATA curves with Polynomial curves on small windows.

This additional attributes generation is done both for the learning data set and for the estimation data set.

1.5. Log data normalization (see step 1.5 on figure 1 and 2.4 on figure 2) (OPTIONAL)

- 10 In order to enhance the generalization performance of the ANN, a pre-processing step consisting of normalizing of the data can be applied. It can consist of one or more of the following computations : Mean - Standard Deviation Normalization, Principal Component Analysis (with retention of the principal components which account for 95 or 98 % of the data), Minimum - Maximum Normalization. Note that this list is not exhaustive.

2. Neural network component

- 20 Several architectures, training algorithms, and methods of implementation are possible for the neural network. The component is a feed-forward MLP (Multi-Layer Perceptron), with an input layer (one neuron per log data attribute), one or several hidden layers, and an output layer (one neuron per CLASS). The outputs $O = (o_1, o_2, \dots, o_N)$ of the ANN have to be the probabilities of each CLASS, according to the current INPUT DATA, and as a consequence have to equal 1 and each belong to the interval $[0, 1]$.

57.0547 U

- 15 -

2.1. Choice of the neural network architecture (see step 1.6 on figure 1 and figures 5a, 5b)

A preferred embodiment of this method is the three-layered
5 neural network, with: sigmoid activation functions; bias; as many nodes on the first layer as there are log attribute inputs, for instance 4; then 10 nodes on the first hidden layer and 10 nodes on the second hidden layer. The number of nodes on the output layer is the same the number of CLASSES.

10

An additional linear matrix K is added to the ANN after the output layer of the neural network. In this case, the last neural layer does not need to have as many nodes as there are CLASSES, but the linear matrix K has to be correctly sized and
15 performing the following operation : $X = K Xh$, where X is a vector of size N (N being the number of CLASSES), Xh is a vector of size Nh coming out from the last neural layer, and K is a matrix of size $N \times Nh$.

20 No matter which ANN architecture is retained, the ANN modules can be combined into a neural network expert committee as shown on figure 5b, step 5b.2.

2.2. Training the ANN (see step 1.7 to 1.10 on figure 1)

25

2.2.1. Evaluation of the network performances at each step (see step 1.8 on figure 1)

Evaluation is realized by computing the global RMSE (Residual
30 Mean Square Error) between the desired outputs as provided by the training or the cross-validation data set, and the actual

57.0547 UK

- 16 -

outputs of the ANN. Two curves corresponding to that training and cross-validation error are displayed and monitored during the training process.

5 2.2.2. Error Back-Propagation (see step 1.7 on figure 1)

The supervised training of the neural network is performed by the Error Back-Propagation, and the algorithm used can be, for instance, Gradient Descent with Adaptative Learning Rate and
10 Momentum. This means that the difference between the expected CLASS probability as provided by the training data set, and the actual current output of the ANN, is propagated backwards through the ANN and the neural weights are accordingly updated. The Adaptative Learning Rate means that this correction is
15 proportional to a learning rate which is tuned accordingly to the evolution of the global RMSE. The Momentum means that a term corresponding to the total sum of the neural weights of the network is added to that global error, with the aim of avoiding the values of those weights increasing too much.

20

 2.2.3. ANN committees (see figure 5b)

Instead of one ANN, one can run several ANN and average their outputs (see step 5b.3). The training of each ANN module of that
25 committee is done thanks to a bootstrap procedure (see step 5b.1), which consists of slightly altering the training set for each ANN (different partition of INPUT DATA samples between the training set and the cross-validation set), and randomly initializing the neural weights of the ANN before training. The
30 generalization abilities of the ANN are then enhanced.

57.0547 UR

- 17 -

2.2.4. Training of the K matrix by Kalman filtering (see figure 5a)

This K matrix is trained in the following way:

- 5 o At each epoch of the training, a first run of the ANN through all the INPUT DATA samples is realized.
- o As a result a matrix M_h is computed. Each row X_h of that matrix corresponds to the outputs of the last layer of the ANN, for a given INPUT DATA sample.
- 10 o The training data set is a matrix M_t where each row corresponds to the CLASS probabilities X_t for a given INPUT DATA sample.
- o The matrix K is approximated by a Kalman-Filtering technique so as to minimize the RMSE of $E = X_t - K X_h$ where
- 15 E and X_t are vectors of size N (N being the number of CLASSES).
- o Once the matrix K is approximated, the Back-Propagation is applied to the ANN for all the training data set samples, and the error is propagated through K first before being
- 20 propagated through the network.

2.2.5. Termination of the training (see step 1.9 and 1.10 on figure 1)

- 25 The end-user chooses on how many training epochs he wants the NN to be trained. The training might stop earlier if the cross-validation error has begun to increase. If the final performances of the ANN are not satisfactory, the end-user can tune the ANN parameters and try a different configuration. One
- 30 can also propose a system where several configurations of the ANN are successively automatically tried and the best one retained.

57.0547 UK

- 18 -

3. The Hidden Markov Model component

3.1. Training of the HMM

5

3.1.1. Automatic training on the cored / geologist defined lithofacies data (see step 1.11 on figure 1)

The CLASS transition probability table depends only on the
10 CLASSES of the learning set and it is therefore an absolute and
static reference. It is computed by counting the successive
CLASS transitions. It cannot be influenced by the neural
predictions, and for a proper application of the Viterbi
15 algorithm, it should be learnt on a large training set of facies
log curves. It is possible to learn the CLASS transition table
on a set of multiple wells, and in this case the CLASS
transitions between two different wells are obviously not taken
into account in the computation of the CLASS transition table.

20 These CLASS transitions can be counted on a sample-by-sample
basis, (i.e. for each INPUT DATA sample), or on a state-to-state
basis, grouping all the samples from the same CLASS together
(see figure 4).

25 A similar automatic computation is done to approximate the CLASS
probability distribution.

30 3.1.2. Geologist-driven correction of the HMM model (see
step 1.12 on figure 1, 2.5 on figure 2, and 3.1 on
figure 3)

57.0547 UK

- 19 -

This correction is performed based on the geologist's expert prior knowledge and can be done after the automatic estimation of the HMM on the learning data set, or before applying the HMM to a specific estimation data set of borehole logs. It relies on the CLASS transition probabilities, (and) the CLASS probability distribution. In case of rock facies classification, it can also rely on the lithofacies bed thickness which the geologist has defined in his geological study.

10 3.2. Combining HMM and ANN

3.2.1. Applying Bayes' Rule (see step 3.2 to 3.4 on figure 3 and 2.6 to 2.7 on figure 2)

15 The ANN posterior CLASS probabilities estimator is designed to work independently from the observation set. Actually, this is a plain classifier, providing the probability $p(x_i)$ for each INPUT DATA sample. However, this can also be expressed as the posterior CLASS probabilities for each input data pattern given
20 the current observation, $p(x_i/y)$.

A HMM model requires three different elements, which are: the state transition probabilities matrix, the state probability distribution, and the observation probability matrix given the
25 current state $p(y/x_i)$. Those three elements are also required for the Viterbi algorithm described below.

In order to get $p(y/x_i)$, one needs to apply the Bayes Rule and to introduce the observation (INPUT DATA) probability
30 distribution and the state (CLASS) probability distribution. However, as the INPUT DATA observations are continuous, and as

57.0547 UK

- 20 -

for each depth step of the Viterbi algorithm that observation probability remains the same for all the possible CLASSES, one can just discard the $p(y)$ value.

- 5 3.2.2. Applying the Viterbi optimization algorithm (see step 3.5 on figure 3 and 2.8 on figure 2)

At this stage, the hybrid ANN / HMM classification system has both a prior CLASS distribution, a CLASS transition probabilities matrix, and the posterior CLASS probabilities matrix, which depend on the time patterns and the observations. The Viterbi algorithm can be applied to those data, provided that the application of Bayes' rule will transform the posterior CLASS probabilities into prior observation probabilities given the previous CLASS and the time pattern.

It can be seen that there is no need to compute the markovian matrix of the observation probabilities given the CLASS. The Viterbi algorithm can therefore directly integrate the time-dependent observation probabilities given the current CLASS and the current time pattern. In other words, the state transition matrix and the state probability distribution have a static behavior (although they can be tuned to the context of the estimation) whereas the observation probabilities, given the previous CLASS, are depth-dependent.

3.2.3. State-to-state or sample-by-sample classes transitions (see figure 4)

30 In case of sample-by-sample classes transitions, the Viterbi algorithm is applied to all the INPUT DATA and associated estimated CLASSES probabilities samples.

57.0547 UK

- 21 -

In case of state-to-state transitions, all the consecutive samples which have in common the same most probable CLASS (see step 4.1), are grouped together (see step 4.2) and considered as an unique observation element. The CLASS probabilities of all the samples belonging to that element are also averaged (see step 4.3), and the Viterbi algorithm is then applied to the groups of observations and not to each observation sample.

- 10 The mean of computing the CLASS probabilities of the observation element can be either a plain mathematical average or a more complex average.

15 In order to perform a state-to-state Viterbi optimization, the state transition probabilities and the state distribution have also to be computed on a state-to-state basis and not on a sample-by-sample basis (see 3.1.1 and step 4.4).

20 After the Viterbi optimization, the observation elements are split into INPUT DATA samples again, and the CLASS curve is displayed on a sample-by-sample basis (see step 4.5).

4. Testing results

25 The simple ANN and the Hybrid ANN / HMM classifiers have been trained and tested on three different sets of geological data. As input data we have used downhole logs, and as classification results, the rock facies classes.

30 4.1. Data set 1 (cored logs)

57.0547 UK

- 22 -

The first data set used for the training contained 490 samples of 4 logs (DT, GR, NPHI and RHOB) and associated core facies (7 facies classes), and were taken from real measurements performed in a well between the depth of 2975 - 3051 m.

5

Once trained, the hybrid system has been tested on the measurements from the same well between depths 2923 - 3161 m, which corresponded to 1562 samples from the same logs.

- 10 Whereas a single ANN system showed an amount of approximately 40 to 45 % correct predictions, the hybrid ANN / HMM system reached an accuracy of 45 to 55 %.

4.2. Data set 2 (cored logs)

15

The data set used for the training contained 3800 samples of 5 logs (DT, GR, NPHI, RT and RHOB) and associated core facies (13 facies classes), and were taken from real measurements performed in 4 wells between the depth of 8000 - 9000 feet.

20

Once trained, the hybrid system has been tested on the measurements from 4 other wells of the same field, where core data were available. The accuracy of the results has been significantly increased, and tests are still currently being
25 performed to assess the effect of several types of additional log attributes.

4.3. Data set 3 (non-cored logs)

57.0547 UK

- 23 -

In this example, the training data set contained about 2000 samples from one well. The testing data set contained between 1500 and 2000 samples per well in a field of 5 wells.

- 5 The lithofacies learning set for the Hybrid ANN / HMM system was provided by the results of electrofacies predictions of an unsupervised neural network classifier. The stability of the predictions of the latter systems has then been compared with the predictions of a plain ANN trained on the same lithofacies
- 10 log curve.

The Hybrid ANN / HMM system is more reliable than a single ANN system in the terms of prediction accuracy and gave less noisy results; it will therefore provide better geological lithofacies

15 log curve estimations.

57.0547 UK

- 24 -

CLAIMS

1. A system for inferring geological classes from oilfield well input data comprising a neural network for inferring class probabilities, characterized in that said system further comprises means for integrating class sequencing knowledge and optimising said class probabilities according to said sequencing knowledge.
2. The system of claim 1, wherein the means for integrating class sequencing knowledge and optimising said class probabilities according to said sequencing knowledge comprises a hidden Markov model.
3. A method for inferring geological classes from oilfield well input data, comprising the following steps:
inferring class probabilities with a neural network;
and
integrating class sequencing knowledge and optimising said class probabilities according to said sequencing knowledge.
4. The method of claim 3, wherein the integrating class sequencing knowledge and optimising said class probabilities according to said sequencing knowledge is achieved according to a hidden Markov model.

57.0547 UK

- 25 -

ABSTRACT

The invention relates to a system for inferring geological
5 classes from oilfield well input data comprising a neural
network for inferring class probabilities. According to the
invention, the system further comprises means for integrating
class sequencing knowledge and optimising said class
probabilities according to said sequencing knowledge.

1/5

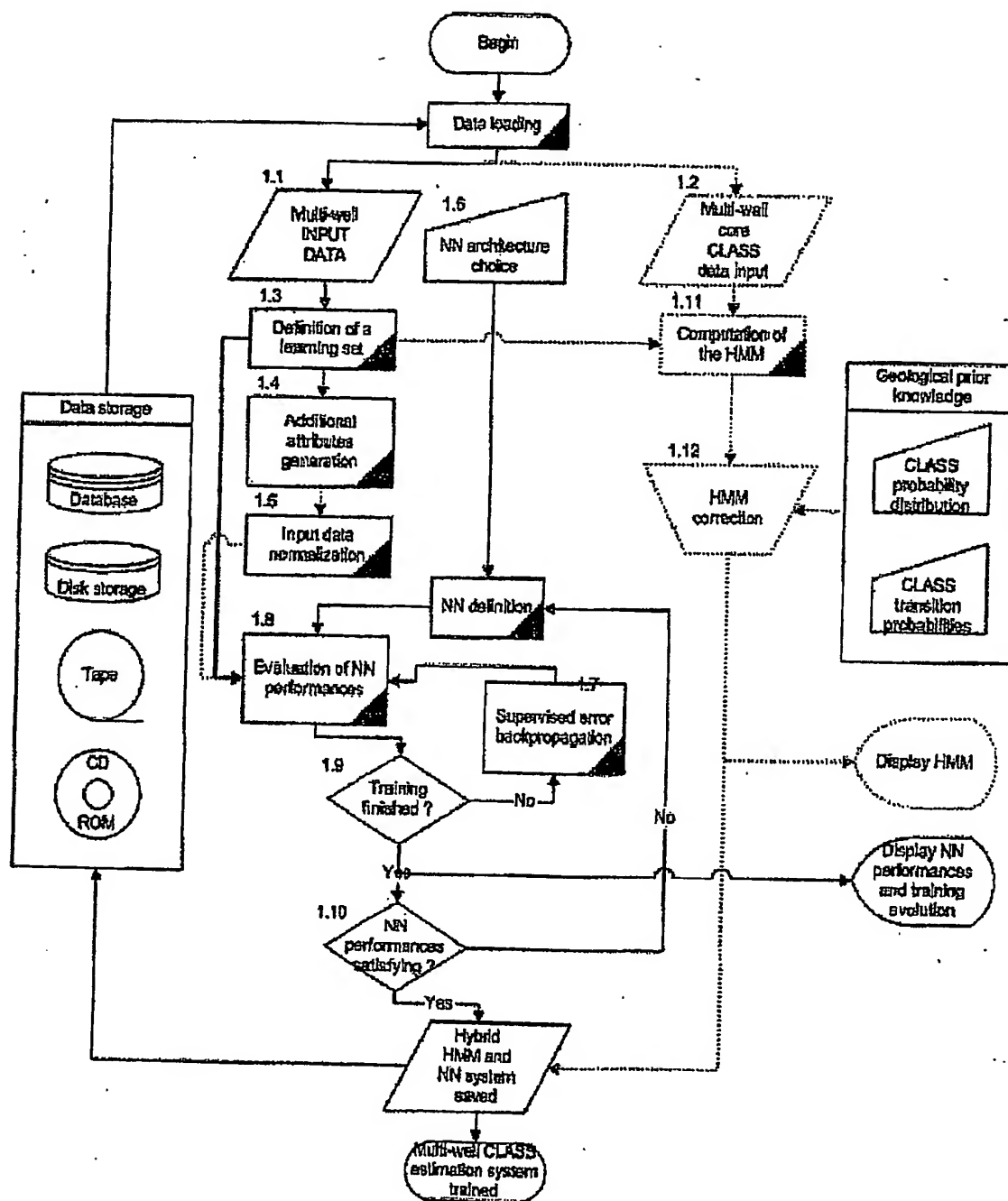


Fig. 1

2/5

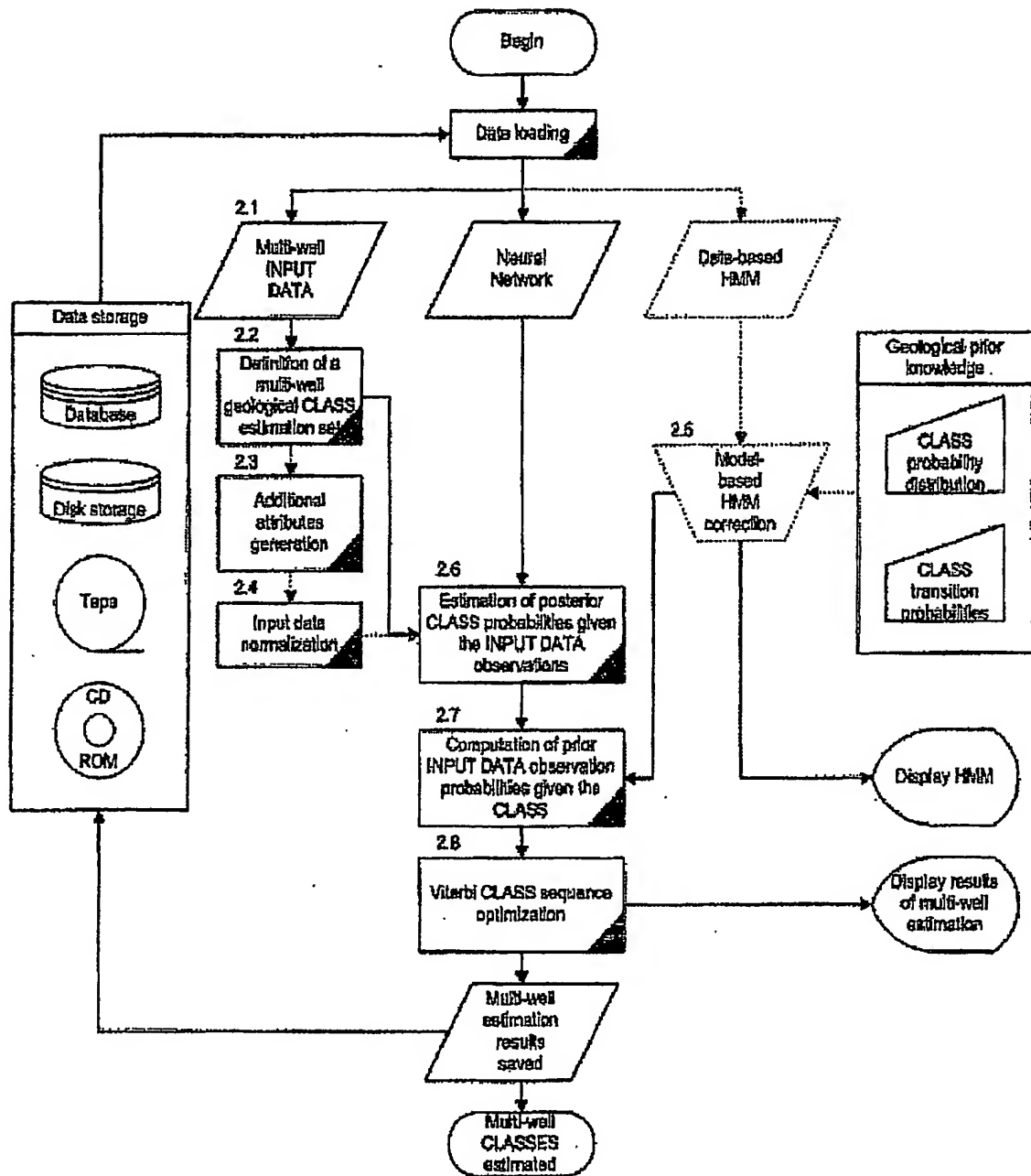


Fig. 2

3/5

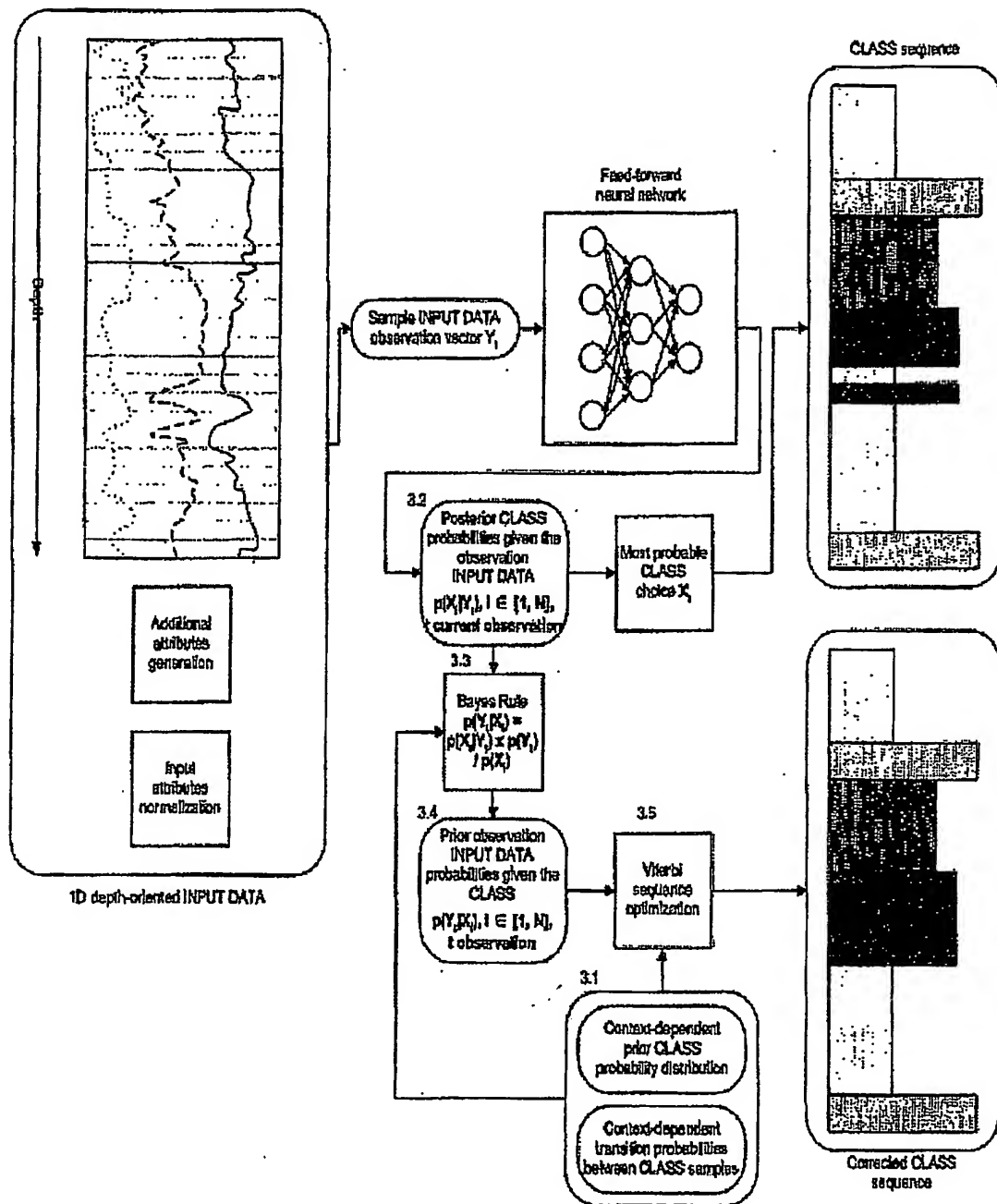


Fig. 3

4/5

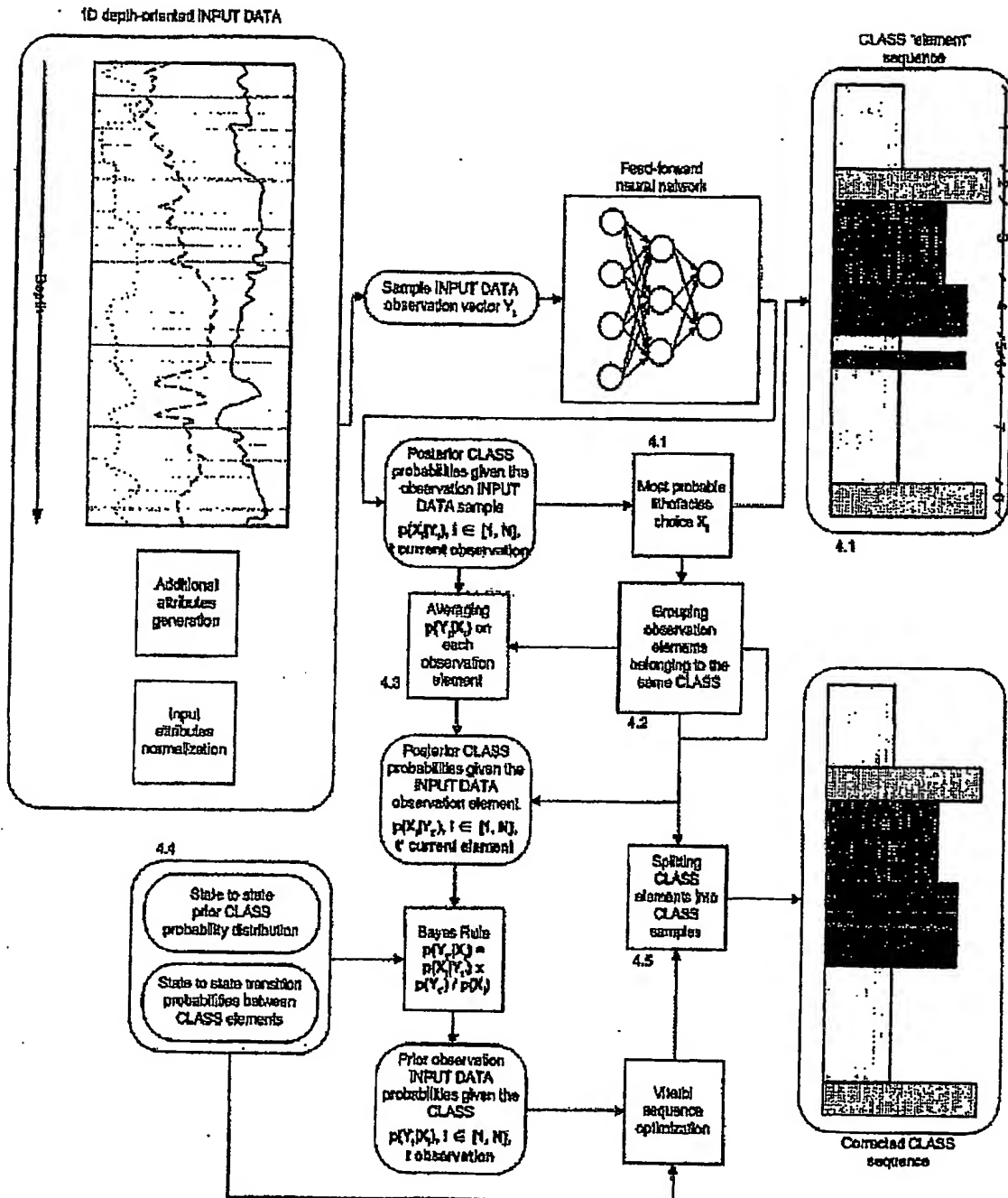


Fig. 4

5/5

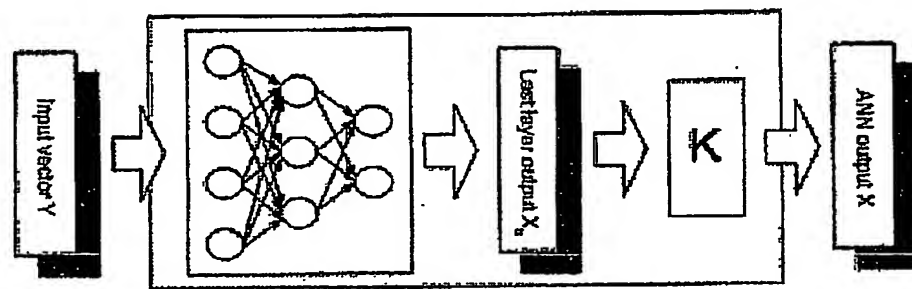


Fig. 5A

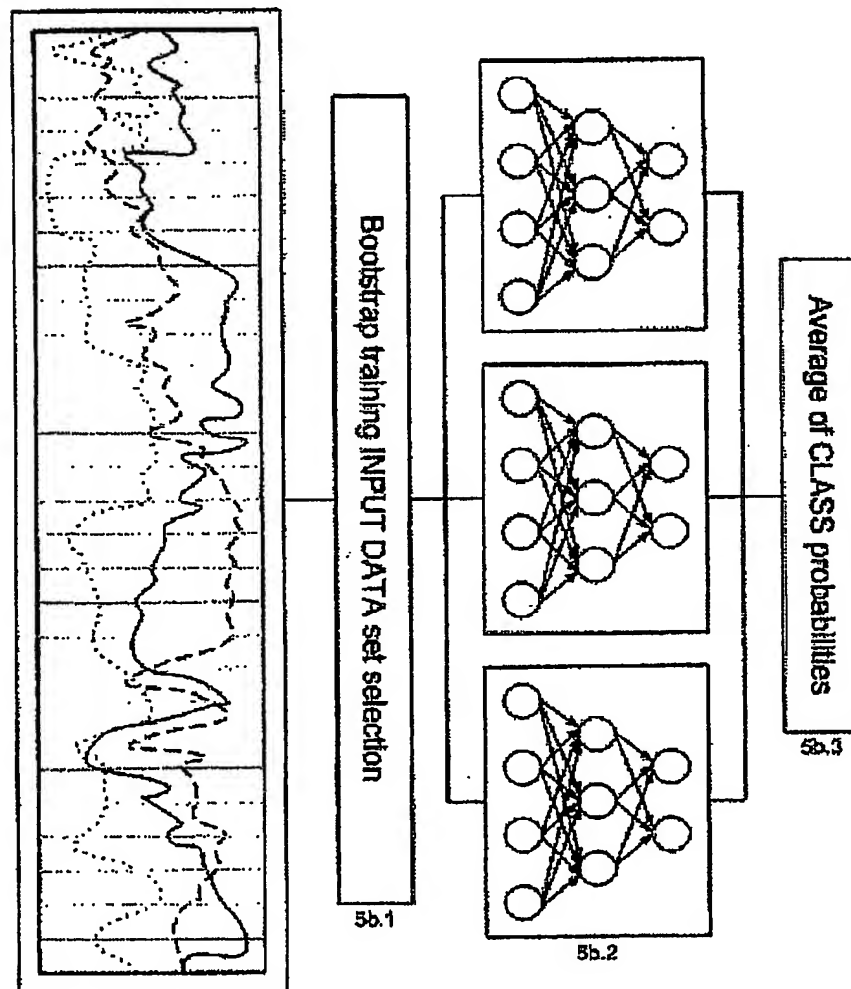
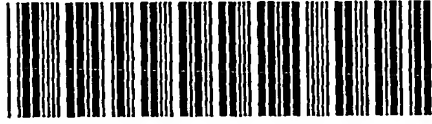


Fig. 5B

PCT Application
PCT/GB2004/000304



**This Page is Inserted by IFW Indexing and Scanning
Operations and is not part of the Official Record**

BEST AVAILABLE IMAGES

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images include but are not limited to the items checked:

- ☐ **BLACK BORDERS**
- ☐ **IMAGE CUT OFF AT TOP, BOTTOM OR SIDES**
- ☒ **FADED TEXT OR DRAWING**
- ☐ **BLURRED OR ILLEGIBLE TEXT OR DRAWING**
- ☐ **SKEWED/SLANTED IMAGES**
- ☐ **COLOR OR BLACK AND WHITE PHOTOGRAPHS**
- ☐ **GRAY SCALE DOCUMENTS**
- ☐ **LINES OR MARKS ON ORIGINAL DOCUMENT**
- ☐ **REFERENCE(S) OR EXHIBIT(S) SUBMITTED ARE POOR QUALITY**
- ☐ **OTHER:** _____

IMAGES ARE BEST AVAILABLE COPY.

As rescanning these documents will not correct the image problems checked, please do not report these problems to the IFW Image Problem Mailbox.